Parallel and Distributed Decision Making Processes: Inference Engine

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***Abstract*-One of the most significant problems in artificial intelligence is knowledge representation linked to the decision-making process in order to simultaneously consider a set of events to achieve the combination that allows the trigger of an action. This work uses a parallel and distributed design approach to represent knowledge, taking a decision-making process during a risk event in an applied engineering process as a case study, which also includes the uncertainty that underlies the process. This allows us to consider the advantages of this kind of knowledge representation. The design is based on innovative fuzzy cognitive maps and their ability to simultaneously consider the causality of all elements that comprise the behavior to be modeled. The approach used by the cognitive model includes: 1) event process; and 2) behavior of the expert in the case study. The analysis utilizes mental models, genetic graphs, and behavioral analysis of the process to identify elements, their causal relationships, and their relative weights.**

Keywords- Knowledge Representation; Initial Scenario; Future Scenario; Fuzzy Cognitive Maps; Decision-Making Process; Reactive Behaviors

I. INTRODUCTION

"Once upon a time there was a robot (Sally, Elvex, Daneel, Mike…) with a positronic brain that coexisted with humans in all kinds of activities, and understood them": this is how robots are portrayed in the science fiction stories of the great Isaac Asimov. Although Asimov admitted that he was mistaken in using positrons as the building block of a robotic brain; however, he was not mistaken was in his vision, which foresaw individuals like Susan Calvin, the robopsychologist of his stories and behavioral designer of positronic brains as well as different designs for brains depending on their activities and superimposed behaviors. Today, the fundamental question is how such behavior brains would be designed. Asimov must have imagined them as planes with level curves or graphs, but they were represented by components that comprised a system and functioned as a whole, in order to produce different representations with behaviors immersed in different contexts.

When one simulates human behavior, the most difficult aspect is to choose a knowledge representation that conforms as closely as possible to its emulation [1]. According to [2], choosing a given type of knowledge representation is an art that must be slowly discovered. As one designs and assembles a representation, one realizes how far we are from imitating the design of the human brain, and subsequently must discover and invent methodologies by which to achieve it. Combining the results of investigations into knowledge representation, cognitive psychology, cognitive engineering, and the new field of emotions and how they affect different behaviors, is a formidable challenge [3-5].

Returning to the romantic ideas of the visionary Asimov, he went so far as to imagine the fractal design of positronic brains [6]. One can think of behavior brain design plans resembling fuzzy cognitive maps, Petri networks or Bayesian networks.

Reference [7] offers an interesting vision in order to define an approach to distributed and parallel modeling of reasoning. This allows us to imagine simulating certain behaviors and connect them through triggers of certain events and thresholds that appear in time. The ability to analyze behaviors through their component elements and the weights of the different causalities that connect them is an innovative vision which forces us to think differently during analysis and design.

This paper presents a promising outlook on this kind of knowledge representation and how it in turn allows the consideration of events arising from an environment fraught with uncertainty and the items of behavior in an instantaneously way, due to characteristics such as parallelism and distribution, all within a study case.

The article is organized as follows: section two provides a brief introduction to fuzzy cognitive maps, for which there is ample literature. Section three describes the domain of the study case. Section four discusses the analysis and design of behavior in the study case, which gives rise to a cognitive model that can be implemented. In section five, we identify the elements that comprise each of the behaviors that will be emulated. With these elements, we move onto section six, where, with the aid of results from the cognitive model described in section 4, we establish the causal relationships between all elements. In section seven, we establish the fuzzy cognitive maps and their causal relationships. Section eight allows us to discuss the simulation of different scenarios, to finally arrive at conclusions.

II. FUZZY COGNITIVE MAPS (FCM)

Fuzzy cognitive maps (FCM) are used as a technique to represent the knowledge of a cognitive model explicated by a cognitive task analysis (CTA) [8]. Kosko introduced these maps in 1986 to describe the behavior of a system in terms of concepts and causal relationships between concepts. Kosko [9, 10], formalizes the causal relationship by proposing fuzzy causal relationships. One of the reasons for including fuzzy logic is to target a partially-focused relationship in relation to the operator between two nodes. Thus, according to Kosko:

Ci = a concept

Qi = a set of linguistic tags (much, more or less, etc.) for Ci

n = number of concepts $0 < i \leq n$

Then, for two concepts, Ci and Cj, Ci causes Cj if

1. $Qi \subset Qj$ & $\neg Qi \subset \neg Qj$ (positive relationship)

2. $Qi \subset \neg Qj$ & $ØQi \subset Qj$ (negative relationship)

A. *Numerical Value of the Causal Relationship of Ci to Cj*

To represent FCMs, we can also use a matrix of adjacency (*n x n*), which includes the values of causal relationship between all concepts. Kosko also included a non-linear function. In other words, *E* (*n x n*) is the matrix of a cognitive map and *C* is a given vector of system status at a given point in time. In this case *Ci*, which is the i^{th} component of vector *C*, denotes the strength of the concept, from which the next status vector can be evaluated as: $C(t+1) = S[C(t)*E]$, where *S* is a non-linear function individually applied to the components of the product of the matrix, and *t* denotes time.

It is important to bear in mind that including non-linearity may force the cognitive map to be recycled through the statuses.

An FCM, therefore, is a digraph that represents concepts as nodes, with the causality relations between them represented by edges (arrows). In order to show these causalities numerically, the edges take on values within the range (0, 1] if the relations are positive, [- 1, 0) if they are negative, and 0 if it is neutral or has no effect [9-15].

FCMs have been used to successfully model different scenarios in which the inference engine draws conclusions in order to arrive at a final decision. The subjects are: a) synthetic emotions for a virtual pet [3]; b) an affective motivational structural link to the inference engine of an intelligent learning system, in order to achieve instructional strategies [16-18];c) a cognitive model which takes into consideration the emotions of a fighter pilot and how they relate to specific behavioral actions of the Red Baron in combat situations [19]; d) the analysis and design of a cognitive emotional assessment model which affects the outputs of the board evaluation function of a computational agent, which plays chess [20, 21].

III. STUDY CASE: SMALL LOCA

The domain to which we applied the cognitive model comprises the first two lines of defense that must be covered in a risk event at a nuclear power plant: the reactor and the primary containment. The study case is the risk event called *small LOCA* and refers to the accident caused by a *small loss of coolant*. Such a loss can cause the plant to malfunction due to the imbalances it produces in system temperature and pressure [22-24].

Alternatively, the decision-making process in a nuclear power plant is a complex process due to the numerous elements involved in its operation and the constant attention demanded by its maintenance. Today, the decision-making process in the plant is analyzed and implemented by a human, using diagram whose main feature is the linear representation of events in a scenario, as shown in Fig. 1. This process is slow and can lead to the appearance of new failures. The primary objective of this paper is to design a cognitive model of knowledge representation and the design of an inference engine that allows data interpretation in order to then take action based on the reflection of a potential situation in an ongoing state. This allows the expert to obtain a preliminary idea that aids the decision-making process to move much faster than it does with the current representation. To automate the inference engine that supports the decision-making process, a final knowledge representation is developed using fuzzy cognitive maps (FCMs). This representation allows the modelling of expert behavior, allowing for uncertainty.

A feature of FCMs is their ability to simulate expert behaviors through cause and effect relationships, which facilitates representation by ensuring the fidelity of causal matrices. When dealing with concurrent events, it is also advisable to use techniques with distributed parallel processing, such as FCMs [12].

SMALL LOCA	PROTECTION SYSTEM OF REACTOR	STEAM SUPPRES-SION SYSTEM	HPCS	RCIC	DEPRE.	CONDENSATE SYSTEM	LPCS	LPCI	SEQUENCE NUMBER	RESULTS OF SEQUENCES
S2	C	SV	U1	U2	X1	V1	V2	V3		
									S2-1 a S2-28	Transfer to pag

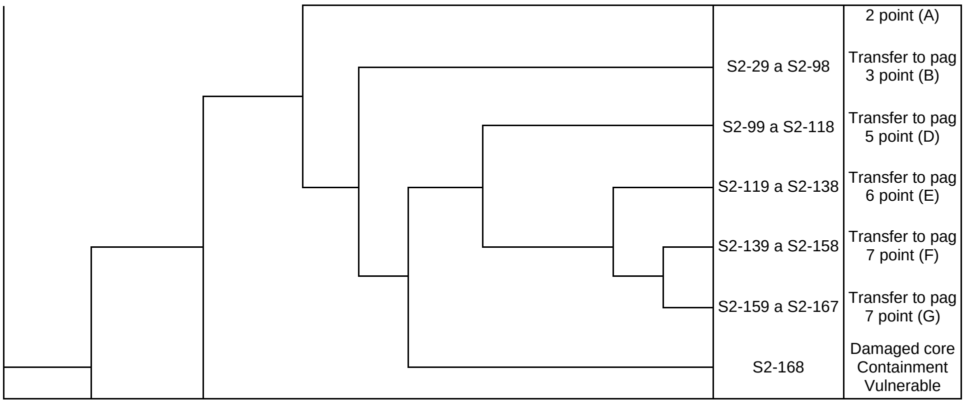

Fig. 1 Event tree of small LOCA (*Loss of Coolant Accident*) (only show one page of 7 [25])

Understanding the *small LOCA* scenario requires a breakdown into three phases, described below [22-24, 26].

a) *Phase 1*: Identify *parameters that indicate the onset of the small LOCA emergency scenario*. The onset of such a scenario necessitates the mitigation of the effects it produces.

b) *Phase 2*: To *mitigate the effects*, it is necessary that the primary *mitigating systems* (cooling systems) such as the *High Pressure Core Spray* (HPCS) be available and operational. To determine the functionality of the system, elements are identified that allow us to indicate the probability of proper operation or failure of the HPCS system.

c) *Phase 3*: In addition to the HPCS, it is necessary to identify other elements that mitigate the effects of a Small LOCA emergency scenario. Knowing how those elements interact allows identification of possible consequence success in mitigating the effects and the satisfactory condition of the core and containment. There is also the possibility of failure in the mitigation systems, with resulting damage to the core and containment.

This paper focuses on the development of phase 3. Phases 1 and 2 were developed in [22, 26], respectively. The following is a description of the elements involved in the Small LOCA event:

i) *Phase 1. Physical Parameters:* Water level in the vessel, pressure in the vessel, reactor power, suppression pool temperature, the primary containment pressure, dry well temperature and water level in the suppression pool.

ii) *Phase 2. HPCS system:* Reactor valve, tank valve, suppression pool valve (manual) and pump.

iii) *Phase 3. Mitigating elements of small LOCA:* relief valve (P); manual valve (01); steam suppressor (SS); HPCS or RCIC (Reactor Core Isolation Cooling System); depressurized (X1); systems operating at low pressure (V); condenser (V1); LPCS (low pressure core spray system, V2); LPCI (low pressure coolant injection, V3); and NSW (nuclear service water-linked LPCI (V4); RHR (residual heat removal, W) using SPC (suppression pool water, W1); SDC (shutdown cooling, W2); and CSC (containment spray cooling; W3); vent (Y); and fugue (R).

The intended function of the systems and elements identified in phase 3 in an emergency is to restore plant operation to a normal state, i.e., to achieve core and primary containment in proper operating conditions [23-25]. The combined work of three or more elements will depend on the success of each of them in mitigating the effects of the small LOCA emergency. Success indicates that the core is in good condition (CG) and the primary containment is stabilized. Sometimes it is not possible to successfully restore a core to proper condition until after undergoing a process of vented or fugue containment. It is even possible that the fugue process can fail (failed containment), and even so, if the mitigating systems survive (SUR) or continue to operate, the core can remain in good condition. We must also consider the possibility of failing to achieve the desired mitigation and obtaining, as a consequence, damage to the core and vulnerability of the primary containment.

Valves P and 01 are related to the high-pressure systems HPCS and RCIC, to help ensure success in mitigation.

On the other hand, unavailability of high-pressure systems such as HPCS (Phase 2) causes activation of depressurizer X1, and when the pressure has dropped, low-pressure systems V (V1 or V2 or V3 or V4) and the heat removal system W (W1 or W2 or W3) immediately go into operation. This causes success in mitigation.

Unavailability of the heat removal system W causes the operation of the depressurizer X1, followed by the activation of the low-pressure system V together with the operation of venting Y. Thus, it is possible to achieve CG with a vented containment. The most critical situation is when the depressurizer X1 or the low-pressure system V fails, because a failure of either causes damage to the core and vulnerability of the containment.

Alternatively, the fact that the mitigating systems continue to operate despite the emergency results in the good condition of the core. If those systems stop operating (do not survive), they would automatically cause damage to the core and the containment could be vented, fugue, failed, or even vulnerable.

A failure in containment ventilation Y causes a fugue process R, resulting in fugue containment. The process of ventilation Y automatically produces a vented containment. A failure of the fugue process R produces a failed containment.

A failure in manual valve 01 causes immediate activation of the heat removal system W. The operation of the heat remover always guarantees a core and containment in good condition.

A failure in relief valve P causes activation of the steam suppressor SS in combination with the heat removal system; this joint action increases the chance of achieving successful mitigation.

The heat removal system W goes into action whenever the reactor pressure has dropped, so that before it operates, the high-pressure system (HPCS, RCIC, or X1) should be operating.

IV. COGNITIVE MODEL

The representation of expert behavior implies the construction of a cognitive model, whose final representation is FCM, and which comprises the following points:

- Mental model of the process;
- Cognitive analysis of tasks;
- Identification of elements or events as units involved in the process;
- Establishment of relationships between such elements or events;
- Development of causal matrices;
- Implementation of fuzzy cognitive maps.

Our case study focuses on the behavior of a supervisor during the decision-making process in order to maintain plant operation within normal standards.

In this task, factual knowledge consists of readings of each of the parameters involved in supervision (Phase 1).

The procedures and strategies in the case study are elucidated in the guide to emergency procedures (GPE) [22-24, 27]. This guide identifies which strategy is the most advisable. It is important to take into account the mental models the expert uses to make a choice, given that, despite the information provided in the guides, there is always a degree of uncertainty inherent to the process.

Cognitive models are procedural and conceptual representations of the expert, obtained from experience, that allow him to use knowledge precisely. Such expertise is elicited using highly diverse representations such as: mental models, graphs, descriptions, basic equations, etc. This produces a cognitive model that allows its representation and implementation [8]. This preliminary analysis and design allows us to choose the best type of knowledge representation from among those provided by artificial intelligence [2], and to finally simulate the cognitive process in an inference engine.

Emulation of expert behavior requires meticulous identification of human expert knowledge, in addition to a representation technique. The typical techniques used to elicit knowledge are not particularly effective because they ignore certain cognitive components. In [8, 28, 29], a procedure is proposed to develop a cognitive model. Applying this methodology determines mental models, to then refine the design by developing cognitive analysis of tasks, which is used to clarify the components necessary to behavioral simulation. We then identify the elements or events that comprise the process and their relationships using genetic graphs. Below, we present a summary of the results obtained, with their representation contained in the following tables and figures.

A. Mental Models of the Case Study

In some cognitive areas, it is possible to formulate theories of competence that specify: what must be calculated, when, and why. Based on such theories, it is possible to then develop a representative algorithm. This area of study is known as theory of competence and is based on mental models. Below we present our formalization of mental models related to the Small LOCA event and represented by Figs. 2, 3, and 4.

Fig. 2 shows the parameters and their conditions (stable or unstable) that determines or rules out the onset of an emergency such as a small LOCA.

Fig. 3 shows the events that determine the functioning or failure of one of the principal mitigating systems (HPCS) in an emergency such as a small LOCA.

If(PoolTempOrWellTempChanges)**Then**
  ContainmentPressureChanges
EndIf

If(ContainmentPressureOscillates)**Then**
  ContainmentLevelUnstable
EndIf

If (PoolLevelChanges) **Then**
WellPressure&WellTempChanges
EndIf

If(PoolTempUnstable)**Then**
PoolLevel&ContainmentUnstable
& Possible Damaged Core
EndIf

If (ContainmentLevelControlled) **Then**
WellPressure&WellTempControlled
& *Core in good condition*
EndIf

If(ReactorPowerVaries)**Then**
ContainmentPressureVaries
EndIf

Dealing with concurrent events, parallel trajectories of action are required **Step 1**

If (PossibleDamagedCore) **Then** **Step 2**
RectorPowerVaries, *Containment unstable & Small LOCA Emergency*
EndIf

Fig. 2 Mental model of parameter analysis (Phase 1)

If (PumpFails (B) or ReactorValveFails (A1) or
(TankValveFails (A2) & PoolValveFails(M))) **Then** **Step 3**
HPCS fails & Vessel in bad condition **Step 4**
Else If (A2 or M) **Then**
HPCS functions & Vessel in good condition
EndElse

Fig. 3 Mental model of mitigating system HPCS (Phase 2)

An event is a fact that indicates that something is happening during a process. For example, to determine the onset of an emergency due to a small LOCA, we observe whether events such as variation in temperature, pressure, or water level occur. To verify the operation of a system such as HPCS, we observe events of failure or proper operation of valves and pumps.

After determining a small LOCA emergency, Fig. 4(a) shows the conditions under which proper conditions of containment and proper condition of the core are achieved, as well as conditions in which mitigation is inadequate, resulting in vulnerability of the containment and damage to the core. Conditions are also determined for proper condition of the core after a process of venting or fugue of the primary containment (Phase 3).

If (small LOCA) **Then** **Step 5**
success = False
Containment = 0
trajectories (success) **Step 6**
EndIf

If (success) **Then** **Step 7**
core in good condition
Else
damaged core
EndIf

If (containment) **Step 8**
Case 0: *Containment vulnerable*
Case 1: *Vented Containment*
Case 2: *Fugue Containment*
Case 3: *Failed Containment*
Case 4: *Containment in good condition*
EndCases

Fig. 4(a) Mental model of small LOCA entry and results (Phase 3)

Success is a logical variable whose value is reached after executing mitigation processes called Paths, and will have a value of True in case of success and False in case of failure.

Containment is a global variable whose value is reached after evaluating the processes of venting (Y) and/or fugue (R). Its value is 0 if the containment is vulnerable, 1 if process Y is executed successfully, 2 if process R is executed successfully, 3 if process R fails, and 4 if the containment is in good condition.

Fig. 4(b) shows the paths, i.e., the potential interactions of mitigating systems to produce success in the function of mitigating the effects of an emergency such as a small LOCA. We also observe the conditions in which the desired success is not achieved (Phase 3).

The mental models obtained evidence the implicit causal relationships between the different events that the expert attends to in managing an emergency such as a small LOCA.

It is important to mention that both the mental model in Fig. 2 and that in Fig. 3 feed the mental models in Figs. 4(a) and 4(b), respectively. Thus the mental model in Fig. 2 indicates whether there is a small LOCA or not, to accordingly develop the mental model in Fig. 4(a), referring to the success or failure of mitigating mechanisms. The mental model in Fig. 3, indicates the availability or unavailability of the primary mitigating system, HPCS, to respond to the emergency. This information is used to produce the mental model in Fig. 4(b).

```
If ((P&01) & (HPCS or RCIC)) Then
    success=True
    Containment=4
EndIf

If (¬HPCS & ¬RCIC) Then
    X1 & V
    W
    success=True
    Containment=4
EndIf

If (¬W ) Then
    X1 y V
    Y
    SUR
    success=True
    Containment=1
EndIf

If (¬V or ¬X1) Then
    success=False
    Containment=0
EndIf

If (¬SUR ) Then
    success=False
EndIf

If (¬Y ) Then
    R
    Containment=2
EndIf

If (¬R) Then
    Containment=3
EndIf

If (¬01) Then
    W
    success=True
    Containment=4
EndIf

If (¬P) Then
    SV & W
    success=True
    Containment=4
EndIf
```

Fig. 4(b) Mental model of small LOCA trajectories (Detailed Step 6) (Phase 3)

B. Cognitive Task Analysis (CTA)

Continuing the methodology proposed by [29], CTA has been used successfully to model both cognitive and physical behavior. CTA is a recursive analysis of tasks, which analyzes the psychological process involved in cognitive construction of ability development; recursively, the task is divided into increasingly specific subtasks, to more accurately identify its component elements. Such subtasks are related to the mental processes that underlie each one. Cognitive analysis of tasks [8, 28, 30, 31] can be summarized by the following points.

- Development Steps: represented by a relationship to the steps in the mental models. Used to discover the different knowledge sets and their relationship to other steps, as well as the interactions between them.
- Contents of steps: indicates the type of knowledge contained by each step.

Thus, the steps in development of mental models are achieved as follows:

- Verify variations of parameters.
- Determine if small LOCA occurs.
- Verify status of elements that comprise the HPCS system.
- Determine if HPCS functions or fails.
- Verify status of mitigating systems (including HPCS).
- Determine mitigating path.
- Determine outcome of mitigation.

C. Genetic Graph

Continuing with the methodology proposed by [29], we now focus on obtaining a genetic graph (GG) represented by Fig. 5. The GG is a tool which represents knowledge (of any kind) grouped into islands and links which relate them. Such links can represent order or inclusion. In this case, we develop only the properties of knowledge representation and their type of linkage, as well as the order or appearance of abilities. The knowledge and abilities represented in the GG are clarified based on the CAT. The links used in this graph are as follows:

1. Class: ***Class*** implies the existence of a conceptual or ability-based hierarchy.

2. Sub-class: ***Sub-class*** implies the existence of levels of granularity in the definition of conceptual or ability-based abstractions.

3. PreCond: implies an order of precedence ***before***.

4. PostCond: implies an order of posteriority, or a knowledge that can be accessed ***after*** covering the knowledge to which it is linked.

5. Comp: component implies that a knowledge or ability is ***made up by*** another component.

6. IsThe/IsA/In: ***IsThe or IsA or In***, represents the description of a specific component depending on the domain in question.

The links between islands determine the relationships between them, and the data of inputs and outputs between them and the different levels of abstraction (which may or may not exist) are explicit. They represent the execution of the expert system.

The types of knowledge observed in the process are represented in the GG based on the type of action to be taken. For example, basic actions or behaviors are derived from procedural knowledge. For basic behaviors, more sophisticated behaviors can be developed [8].

Factual knowledge:

F1: Type of physical parameters

F2: Variations in physical parameters

F3: Pump and valve type

F4: Pump and valve status

F5: Mitigating system type

F6: Mitigating system status

Procedural knowledge:

P1: How parameters affect one another

P2: When an emergency is declared

P3: How the pump and valves affect the mitigating system HPCS

P4: How mitigating systems interact

P5: Determines whether mitigation was a success or failure.

Actions:

A1: Analyze parameters

A2: Analyze HPCS system

A3: Mitigate (analyze mitigating systems and elements)

Finally, using the obtained results, we obtain the design of the cognitive model that represents expert behavior, as shown in Fig. 6. This is based on actions derived from factual and procedural knowledge with the GG (Fig. 5), which allows the establishment of levels in the behavioral diagram. The objective of this behavior is to restore plant operation (core and containment) to a normal state (a balance of levels of physical parameters), in response to an event like a small LOCA. The human expert takes into consideration the GPEs and statuses of physical parameters, so that in the case of any variation, they can conduct analysis of parameters (Level 2). As part of this analysis, the expert considers the relationships between the different parameters, and the effect that each of them exerts upon the others. Based on such relationships, the existence of an emergency like a small LOCA (Level 2) is determined. If there is no emergency, the expert merely continues to monitor the operation of the plant without taking any other action. If there is a small LOCA, it is necessary to implement a process to mitigate the effects produced by the event. As part of this process, it is necessary to determine the availability of the HPCS system as the principal mitigating system based on the operation of valves and a suction pump (Level 1). It is also necessary to determine the availability of other systems and mitigating elements, for which the expert considers the relationships between them and their effects on the mitigation process. During this process, a mitigation path (Level 0) is defined with the aid of the GPEs and technical system guides. As a result of the process, the success or failure of the mitigating systems (Level 0) in achieving the primary objective is determined, i.e. the restoration of the operational balance of the plant with the core and containment in good condition.

The ability to represent this behavior implies the development of three FCMs, one for each level determined by the actions (three phases): A1 (analyze parameters), A2 (analyze HPCS system), and A3 (mitigate, i.e., analyze systems and mitigating elements). Each map will explicitly display the relationships between the events involved at each level.

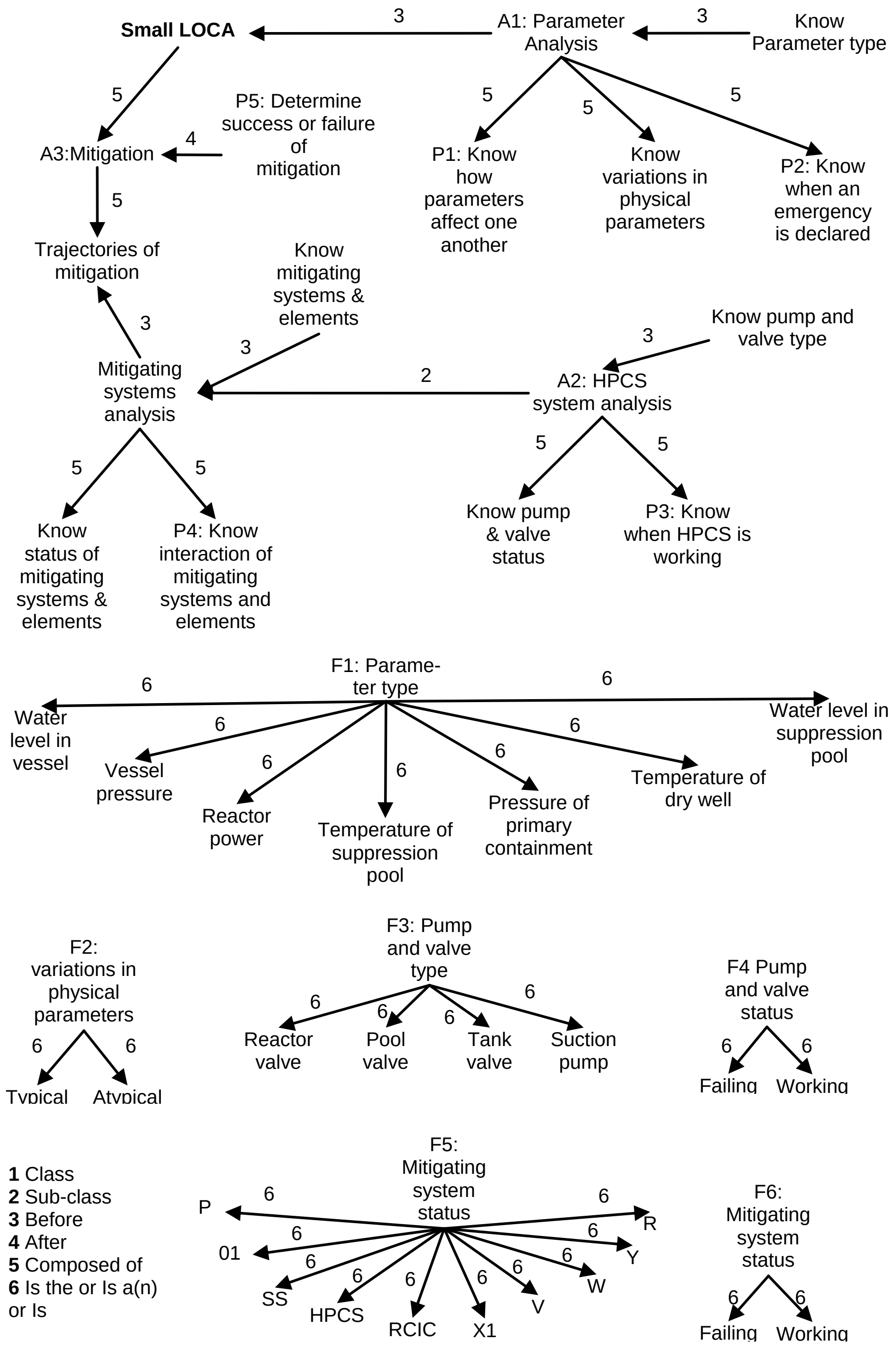

Fig. 5 Genetic graph

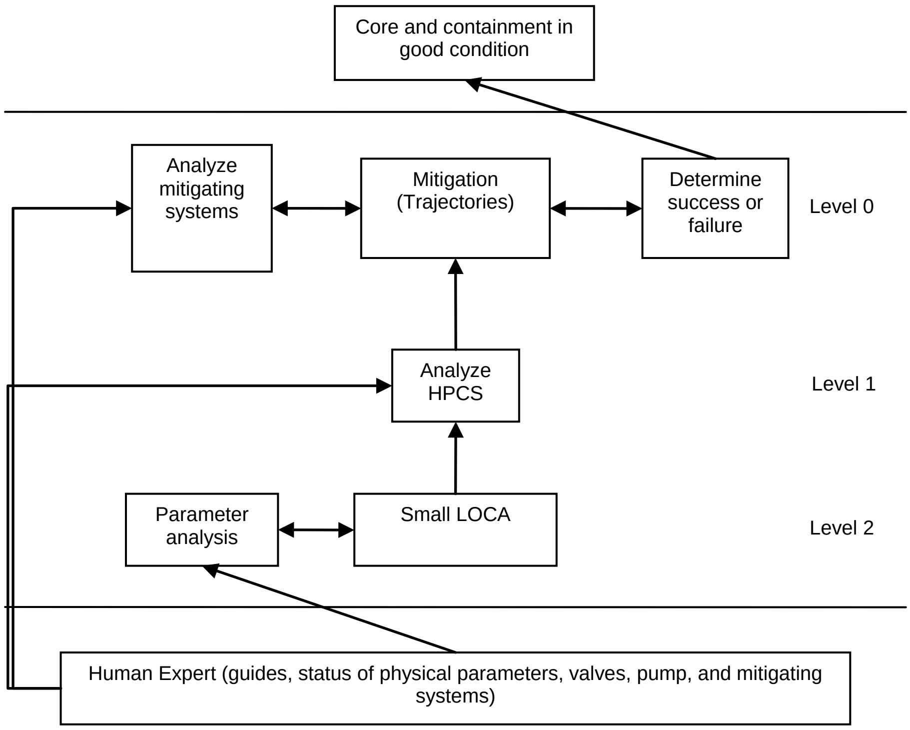

Fig. 6 Behavioral diagram of small LOCA

V. IDENTIFICATION OF EVENTS REPRESENTED IN COGNITIVE MODEL

The CTA provides the basis for identification of the events that comprise each of the fuzzy cognitive maps to be developed based on the results obtained in section 4.1. These are represented by the nodes in the causal matrices.

A. Events Identified Based on Parametric Analysis

Factual knowledge F1 (type of parameters) and F2 (variations in physical parameters) allow identification of events which, intervene in a small LOCA based on expert behavior (the mental model shown in Fig. 2). These events are represented by means of nodes. Such events comprise the elements (Table 1) in the first cognitive map.

TABLE 1 EVENTS IDENTIFIED IN THE PARAMETRIC ANALYSIS (LEVEL 2)

1	VWL (Water level in the vessel outside the acceptable range)
2	VP (Vessel pressure outside the acceptable range)
3	RP (Reactor power outside the acceptable range)
4	SPT (Suppression of pool temperature outside the acceptable range)
5	DWT (Dry well temperature outside the acceptable range)
6	PCP (Primary containment pressure outside the acceptable range)
7	PWL (Water level in the suppression pool out of range)
8	RG (Reactor in good condition)
9	PCS (Primary containment stabilized)

B. Events Identified Based on Analysis of the HPCS System

Based on factual knowledge F3 (pump and valve type) and F4 (pump and valve status) from the mental model shown in Fig. 3, the following six events are identified, which comprise the second map and are represented in Table 2.

TABLE 2 EVENTS IDENTIFIED HPCS SYSTEM ANALYSIS (LEVEL 1)

1	A1 (Reactor valve failure)
2	A2 (Tank valve failure)
3	M (Manual valve failure of suppression pool)
4	P (Pump failure)
5	HPCS operational
6	Vessel in good condition

C. Events Identified Based on Analysis of Mitigating Systems and Elements (Small LOCA)

Factual knowledge F5 (types of mitigating systems) and F6 (status of mitigating systems) from the mental model shown in Fig. 4 allow identification of events (Table 3) to develop the third cognitive map.

TABLE 3 EVENTS INVOLVED IN MITIGATION OF SMALL LOCA (LEVEL 0)

1	Relief valve closure	P
2	Operator opens the valve to be available condenser	01
3	Steam suppressor	SS
4	HPCS operational	HPCS
5	RCIC operational	RCIC
6	Depressurized	X1
7	Condenser (V1), LPCS (V2), LPCI (V3) & NSW linked LPCI (V4)	V
8	RHR: functions RHR SPC (W1), RHR SDC (W2) and RHR CSC (W3)	W
9	Vent	Y
10	Fugue	R
11	Survival systems	SUR
12	Core in good condition	CG
13	Vented containment	VT
14	Fugue containment	FG
15	Failed containment	FL
16	Vulnerable containment	VN

Generally, the operation of a nuclear power plant consists of generating electricity from steam obtained by heating water by the reactor core. Therefore, keeping the reactor operational in a failure scenario involves activating systems that mitigate the failure scenario [14, 15, 23-26]. Mitigating systems and mechanisms are described in Table 3, which represents the events identified in the process. The failure scenario consists of mitigating the loss of coolant, and is identified with the name small LOCA [22-26, 32].

VI. ESTABLISHMENT OF RELATIONSHIPS BETWEEN INVOLVED EVENTS

Relationships of causality between the different events in the process were established based on the cognitive model previously obtained. The established relationships may be of positive or negative causality.

Positive causality: The effect of an increase in one of the elements causes a proportional increase in another, and similarly a decrease in one causes a proportional drop in another. For example, an increase in pressure in the primary containment causes an increase in temperature. Positive causality also implies the effect of a node upon increasing the property of another node. Thus, an event in the process can have positive causality on another; if, for example, the pool water level is within a normal operating range, then core temperature will tend to stabilize within the normal operating range.

Negative causality: The effect of an increase in one element causes a proportional drop in another or vice-versa: a decrease in one causes a proportional increase in another. For example, a drop in temperature in the reactor vessel can produce an increase in power. Negative causality also refers to the contrary effect one event has upon another, i.e., an event can cause a drop in the property represented by another event. In the case of a negative causality the effect would be to induce a variable out of the normal operating range, regardless of whether it goes above or below said range.

To indicate these causalities numerically, the relationships represented by edges (arrows) take values in the range (0, 1] if it is positive, [-1, 0) if it is negative, and 0 if it is neutral or there is no effect [11, 33].

A. Relationships of Causality between Events Identified in Parametric Analysis

Accordingly, we have the following relationships of causality between the events identified:

The nine events identified in Table 1 have relationships among themselves, as shown in the mental model in Fig. 2, in the genetic graph in Fig. 5 and the behavioral graph in Fig. 6.

Based on the mental model obtained from reactor and primary containment control procedures, relationships of positive or negative causality between one node and another are established.

Temperature out of range: defined as a temperature which varies from that established in normal operating conditions.

Pressure out of range: defined as a pressure which varies from that established in normal operating conditions.

Level out of range: defined as a level which varies from that established in normal operating conditions.

Details of how these relationships are obtained are presented by [22-24], and are summarized in Table 4.

TABLE 4 RELATIONSHIPS BETWEEN EVENTS IDENTIFIED IN PARAMETRIC ANALYSIS

Causality	Value
1) Positive between SPT and PCP	1
2) Positive between DWT and PCP 3) Implicitly positive between SPT and DWT because of the relationship they both have about PCP	1 1
4) Implicitly negative between PWL and PCP derived from 2)	-1
5) Negative between VWL and VP	-1
6) Negative between VP and RP 7) Implicitly negative between RP and VWL because a higher level of water in the vessel (VWL) means a decrease in RP	-1 -1
8) Negative between VWL and RG because it would not ensure adequate core cooling	-1
9) Implicitly negative between VP and RG	-1
10) Negative between SPT and PWL	-1
11) Negative between SPT and PCS 12) Negative between DWT and PCS 13) Negative between PWL and PCS 14) Negative between PCS & PCP, derived from 10), 11) & 12)	-1 -1 -1 -1
15) Negative between VWL and DWT	-1
16) Positive between PCS and RG 17) Positive between RP and RG 18) Implicitly negative between SPT and RP	1 1 -1

B. Relationships between Events Identified in HPCS System Analysis

From the mental model represented by Fig. 3 and the conceptual and behavioral diagrams represented by Figs. 5 and 6, respectively, relationships are obtained between events in Table 2, which are described in [23, 24, 26]. The relationships between these events are summarized in Table 5.

TABLE 5 RELATIONSHIPS BETWEEN EVENTS IDENTIFIED IN HPCS SYSTEM ANALYSIS

Event	Causality	Value
A1	1) Negative about A2, M, HPCS and Vessel	-1
A2	2) Negative about A1 and P 3) Negative about HPCS	-1 -0.5
M	4) Negative about A1 y P 5) Negative about HPCS	-1 -0.5
P	6) Negative about A2, M, HPCS and Vessel	-1
HPCS	7) Negative about A1, A2, M, P 8) Positive about Vessel	-1 1
Vessel	9) Negative about A1, A2, M and P 10) Positive about HPCS	-1 1

C. Relationships between Events in the Small LOCA Scenario

The proposal associates each potential event with a possibility, which allows a decision-making process to be achieved based on the status of the parameters that form part of the various initiating events or the potential paths created in the small LOCA scenario. From the mental model represented by Figs. 4(a) and 4(b) and the conceptual and behavioral graphs in Figs. 5 and 6, respectively, following relationships between events in the small LOCA scenario are obtained, as shown in Table 3. These relationships are described below:

- **Valves P and 01** jointly with the high-pressure systems **(HPCS or RCIC)** provide for **success in mitigation**. **RCIC comes online only when HPCS fails**. This implies the presence of the following relationships of causality:
  - *Positive* between: CG and HPCS; 01 and P; 01 and CG-VN; HPCS and CG-FL; and P and CG-VN.
  - *Negative* between: RCIC and HPCS; CG and VN; HPCS and VN; VN and CG; and VN and HPCS.
- Unavailability of the high-pressure **HPCS** system **activates the RCIC and the depressurizer X1**; when the pressure drops, the low-pressure systems **V and the heat removal system W** are activated immediately**, causing success in mitigation.** This implies the establishment of the following relationships of causality:
  - *Positive* between: X1 and V; W and CG; V and X1; CG and W; X1 and CG-VN; and V and CG-FL.
  - *Negative* between: X1 and HPCS; V and HPCS; V and VN; W and VT-VN; HPCS and RCIC; HPCS and X1; HPCS and V; and VT-FL and W.

- The **unavailability** of the heat removal system **W causes activation of the depressurizer X1**, thus activating the low-pressure system **V jointly with the operation of venting Y**. This allows the **CG with vented containment**, creating the following relationships of causality:
  - *Positive* between: Y and VT.
  - *Negative* between: Y and W; VT and W; W and SUR (SURvive sytems); SUR and W; and W and VT-VN.
- The most critical situation is when the **depressurizer X1 or the low-pressure system V fails,** because a failure of either **causes damage to the core and vulnerability of the containment.** This implies the establishment of the following relationships of causality:

- Negative between: VN and X1; VN and V; and VN and CG-VL.

- Alternatively, when the systems **continue to operate despite a small LOCA, CG results.** If these **systems do not survive,** they automatically cause **damage to the core, and the containment could be vented, fugue, fail, or even become vulnerable.** Consequently, the following relationships of causality are established:
  - *Positive* between: SUR and CG and CG and SUR.
  - *Negative* between: SUR and VN.
- The process of **ventilation Y** automatically produces a **vented containment.** This produces the following relationships of causality:
  - *Positive* between: Y and VT; VT and Y.
  - *Negative* between: Y and VN.
- A **failure in ventilation Y** of the containment **produces a process of fugue R**, causing a **fugue containment**. This implies the establishment of the following relationships of causality:
  - *Positive* between: R and FG and FG and R.
  - *Negative* between: R and Y; R and VT; R and W; R and VN; FG and VT; FG and Y; FG and VN; Y and R; Y and FG; Y and FL; VT and R; VT and FG; and VT and FL.
- A **failure in the fugue process R** produces a **failed containment**, creating the following relationship of causality:
  - *Negative* between: FL and R; FL and FG; FL and VT; FL and Y; FL and VN; and R and FL.
  - A **failure in manual valve 01 causes the heat removal system W** to be **activated immediately**. The **operation of W guarantees a CG and containment in good condition**. *Positive* between: W and CG.
  - *Negative* between: W and VT; W and FG; W and FL; and W and VN.

The established relationships are summarized in Table 6.

TABLE 6 RELATIONSHIPS BETWEEN EVENTS OF SMALL LOCA

Event	Causality	Value
P	1) Negative about SS 2) Positives about CG-VN	-1 0.33
01	3) Positive about P 4) Negative about SS 5) Positivas about CG-VN	1 -1 0.66
SS	6) Negative about P, 01 7) Positive about CG-VN	-1 0.33
HPCS	8) Negative about RCIC, X1, V, VN 9) Positive about CG-FL	-1 0.66
RCIC	10) Negative about HPCS	-1
X1	11) Negative about HPCS 12) Positive about V 13) Positive about CG-VN	-1 1 0.66
V	14) Negative about HPCS, VN 15) Positive about X1 16) Positive about CG-FL	-1 1 0.66
W	17) Positive about CG 18) Negative about SUR, VT-VN	1 -1
Y	19) Negative about W, R, FG, FL, VN 20) Positive about VT	-1 1
R	21) Negative about W, Y, VT, FL, VN 22) Positive about FG	-1 1
SUR	23) Negative about W, VN 24) Positive about CG	-1 1
CG	25) Negative about VN 26) Positive about HPCS, W, SUR	-1 1
VT	27) Negative about W, R, FG, FL, VN 28) Positive about Y	-1 1

FG	29) 30)	Negative about W, Y, VT, FL, VN Positive about R	-1 1
FL	31)	Negative about W, Y, R, VT, FG, VN	-1
VN	32)	Negative about HPCS, X1, V, CG, VT, FG, FL	-1

- A **failure in relief valve P causes the steam suppressor SS to** be activated **along with the heat removal system**; this joint action **increases the chance of achieving a successful mitigation**.

- *Positive* between: SS and CG-VN.

- *Negative* between: SS and P; SS and 01; P and SS; 01 and SS.

- The heat removal system **W is activated whenever** the reactor **pressure drops** so that before it operates, any of the high-pressure systems (**HPCS, RCIC or X1) must be operating**.

VII. FUZZY COGNITIVE MAP AND MATRIX OF RELATIONSHIPS

This section presents the development of fuzzy cognitive maps based on the relationships established in the preceding section.

Fuzzy cognitive map (FCM): expressed with a diagram containing the identified events, represented by nodes and the causal relationships established between them, represented by edges. The neutral or zero relationship of causality is not drawn in the diagram; only negative or positive causalities are represented. The nodes acquire values in the interval [0, 1], which indicate the value of the status of the events represented by the nodes.

Matrix of causality: a matrix representing the values of positive or negative causality between each of the nodes that comprise the FCM, with the information obtained from the cognitive model. The matrix can be constructed without considering a specific order, and the analytical result is not affected.

A. FCM and Matrix of Causality Which Represent the Parametric Analysis

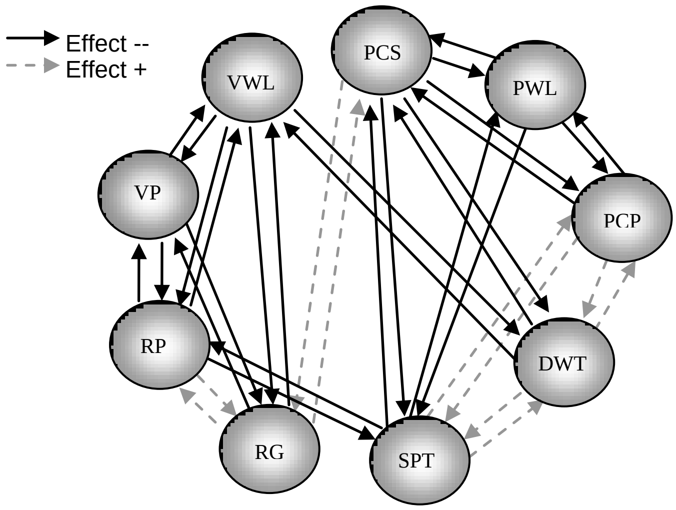

Fig. 7 FCM of parametric analysis

TABLE 7 CAUSAL MATRIX OF RELATIONSHIPS BETWEEN EVENTS IDENTIFIED IN PARAMETRIC ANALYSIS

	VWL	VP	RP	SPT	DWT	PCP	PWL	RG	PCS
VWL	0	-1	-1	0	-1	0	0	-1	0
VP	-1	0	-1	0	0	0	0	-1	0
RP	-1	-1	0	-1	0	0	0	1	0
SPT	0	0	-1	0	1	1	-1	0	-1
DWT	-1	0	0	1	0	1	0	0	-1
PCP	0	0	0	1	1	0	-1	0	-1
PWL	0	0	0	-1	0	-1	0	0	-1
RG	-1	-1	1	0	0	0	0	0	1
PCS	0	0	0	-1	-1	-1	-1	1	0

B. FCM and Matrix of Causal Relationships That Represent the HPCS System

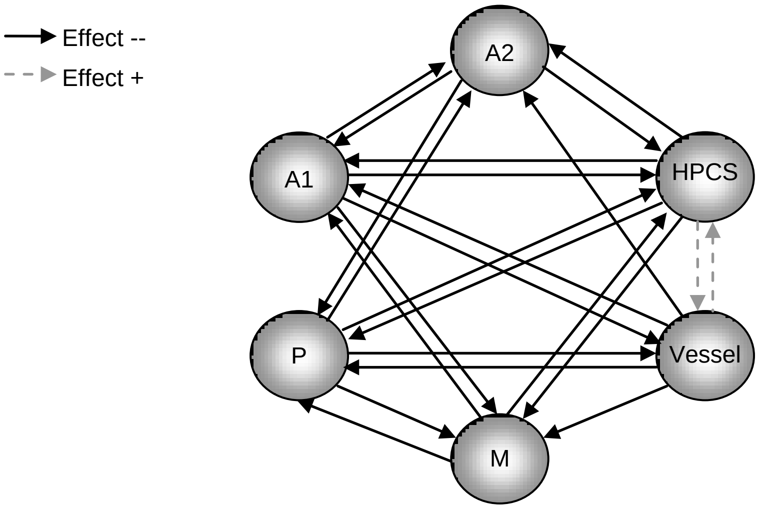

Fig. 8 FCM of HPCS system

TABLE 8 CAUSAL MATRIX OF RELATIONSHIPS BETWEEN EVENTS IDENTIFIED IN HPCS SYSTEM ANALYSIS

	A1	A2	M	P	HPCS	Vessel
A1	0.000000	-1.000000	-1.000000	0.000000	-1.000000	-1.000000
A2	-1.000000	0.000000	0.000000	-1.000000	-0.500000	0.000000
M	-1.000000	0.000000	0.000000	-1.000000	-0.500000	0.000000
P	0.000000	-1.000000	-1.000000	0.000000	-1.000000	-1.000000
HPCS	-1.000000	-1.000000	-1.000000	-1.000000	0.000000	1.000000
Vessel	-1.000000	-1.000000	-1.000000	-1.000000	1.000000	0.000000

C. FCM and Matrix of Causal Relationships Representative of the Small LOCA Scenario

To quantify the causal link (positive or negative) all possible interactions of the mitigating systems are considered in order to produce resulting success to mitigate the effects of the emergency small LOCA. Additionally, the conditions under which the desired success does not occur are observed. A ratio of 0.33 indicates the possibility that an element interacts with another to mitigate the small LOCA.

The FCM is shown in Fig. 9, and its corresponding matrix of relationships is detailed in Table 9.

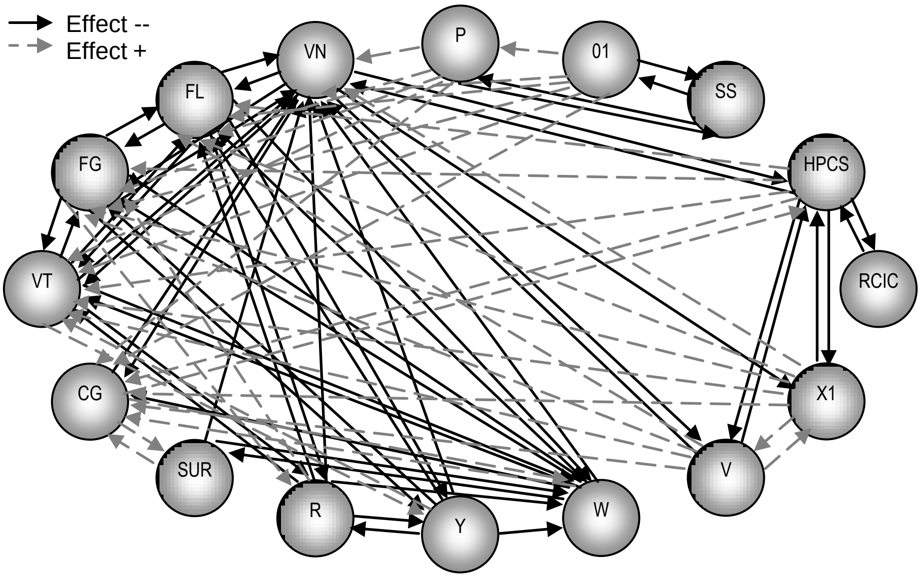

Fig. 9 FCM of small LOCA

TABLE 9 CAUSAL MATRIX OF RELATIONSHIPS BETWEEN EVENTS IDENTIFIED IN SMALL LOCA ANALYSIS

	P	**01**	**SS**	**HPCS**	**RCIC**	**X1**	**V**	**W**	**Y**	**R**	**SUR**	**CG**	**VT**	**FG**	**FL**	**VN**
P	0	0	-1	0	0	0	0	0	0	0	0	0.33	0.33	0.33	0.33	0.33
01	1	0	-1	0	0	0	0	0	0	0	0	0.66	0.66	0.66	0.66	0.66
SS	-1	-1	0	0	0	0	0	0	0	0	0	0.33	0.33	0.33	0.33	0.33
HPCS	0	0	0	0	-1	-1	-1	0	0	0	0	0.66	0.66	0.66	0.66	-1
RCIC	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0
X1	0	0	0	-1	0	0	1	0	0	0	0	0.66	0.66	0.66	0.66	0.66
V	0	0	0	-1	0	1	0	0	0	0	0	0.66	0.66	0.66	0.66	-1
W	0	0	0	0	0	0	0	0	0	0	-1	1	-1	-1	-1	-1
Y	0	0	0	0	0	0	0	-1	0	-1	0	0	1	-1	-1	-1
R	0	0	0	0	0	0	0	-1	-1	0	0	0	-1	1	-1	-1
SUR	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	-1
CG	0	0	0	0.33	0	0	0	0.33	0	0	0.33	0	0	0	0	-1
VT	0	0	0	0	0	0	0	-1	1	-1	0	0	0	-1	-1	-1
FG	0	0	0	0	0	0	0	-1	-1	1	0	0	-1	0	-1	-1
FL	0	0	0	0	0	0	0	-1	-1	-1	0	0	-1	-1	0	-1
VN	0	0	0	-1	0	-1	-1	0	0	0	0	-1	-1	-1	-1	0

VIII. SIMULATIONS AND DISCUSSION OF RESULTS

The simulation of the decision-making process during supervision of the reactor in response to a potential emergency such as a small LOCA consists of proving three scenarios, each of which corresponds to one of the phases described in section 3.

In each of the test scenarios, there is an initial vector (representing the status of the different events that make up the FCM); the vectors resulting from the iterations indicated (V_1 – V_8 on average); and a final vector, whose value constitutes the status of each of the nodes in a future scenario.

An interpretation of results is made based on the following criteria:

$S(x) \leq$ 0.337, equal to 0.

0.455 $\leq S(x) \leq$ 0.55, equal to 0.5

$S(x) \geq$ 0.79, equal to 1

where

0 indicates that the characteristic of the process represented by the node is null;

0.5 indicates that the characteristic of the process represented by the node is 50% present;

1 indicates the characteristic of the process represented by the node is 100% present.

The range is set according to the results for all possible scenarios. The scenarios, which by the nature of the model are impossible to manifest, are discarded. For example, the scenario in which CG (core in good condition) and VT (vented contention) are present, both are mutually exclusive and are therefore impossible to manifest.

Below, tests performed with the FCMs in Figs. 7, 8, and 9 are detailed, for which the matrices of causal relationships are represented by Tables 7, 8, and 9, respectively.

A. Test Scenario for Parametric Analysis (Phase 1)

In this first scenario, analysis of the different physical parameters through the first FCM is conducted after observing the status of those parameters. The status is represented by a vector indicating the initial value of each of the events related to such parameters; in this case SPT (suppression of pool temperature outside the acceptable range) is the only event with value 1; the other events have an initial value of zero, indicating that the event occurring is SPT. The test results of parametric analysis are shown in Table 10.

Initial Vector	VWL	PV	RP	SPT	DWT	PCP	PWL	RG	PCS
V_1	0	0	0	1	0	0	0	0	0

TABLE 10 TEST RESULTS OF PARAMETRIC ANALYSIS

	VWL	VP	RP	SPT	DWT	PCP	PWL	RG	PCS
V_1	0.000000	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000
V_2	0.500000	0.500000	0.006693	0.500000	0.993307	0.993307	0.006693	0.500000	0.006693
V_3	0.000045	0.006474	0.006693	0.999946	0.992847	0.999389	0.000553	0.007153	0.000047
V_4	0.006269	0.482643	0.006716	0.999951	0.999954	0.999953	0.000046	0.500275	0.000000
V_5	0.000048	0.071339	0.007083	0.999953	0.999953	0.999955	0.000045	0.082339	0.000004
V_6	0.003008	0.389991	0.007069	0.999953	0.999955	0.999955	0.000045	0.420310	0.000000
V_7	0.000113	0.104151	0.007666	0.999953	0.999954	0.999955	0.000045	0.126790	0.000003
V_8	0.002040	0.337860	0.007487	0.999953	0.999955	0.999955	0.000045	0.381550	0.000001
V_9	0.000178	0.123968	0.008232	0.999953	0.999954	0.999955	0.000045	0.159485	0.000002
V_{10}	0.001565	0.301646	0.007978	0.999953	0.999955	0.999955	0.000045	0.359034	0.000001
V_{11}	0.000238	0.136710	0.008831	0.999953	0.999954	0.999955	0.000045	0.186008	0.000002
V_{12}	0.001283	0.273809	0.008540	0.999953	0.999955	0.999955	0.000045	0.345116	0.000001
V_f	0.000292	0.144960	0.009474	0.999953	0.999954	0.999955	0.000045	0.208704	0.000002

Applying the criteria of interpretation, we obtain the following final vector (V_f):

	VWL	PV	RP	SPT	DWT	PCP	PWL	RG	PCS
V_f	0	0	0	1	1	1	0	0	0

The values 0 and 1 are interpreted as null and 100%, respectively, of the presence of the event during the process represented by this particular node.

This is the potential future scenario, in which the events SPT (suppression of pool temperature), DWT (dry well temperature), and PCP (primary containment pressure) have the value 1, while the others are of value 0, including the events RG (reactor in good condition) and PCS (primary containment stabilized). This indicates that when the dry well temperature is out of range, it produces a pressure out of range in the primary containment, which results in destabilization of the primary containment and reactor failure.

B. Test Scenario for the HPCS System (Phase 2)

The result of the first phase determines the need to mitigate its negative effect for the stability of the reactor, indicating that it is necessary to enter the phase 2 simulation based on the test scenario for the HPCS system, one of the principal mitigating systems. In this scenario, the HPCS system is analyzed through the second FCM; the first FCM determines the trigger for the operation of the second FCM. The HPCS system is represented by a vector which indicates the status of each of its elements as present or absent events. In this scenario, the presence of event A1 (reactor valve failure) is indicated. The test results 1 of HPCS System Status are shown in Table 11.

TABLE 11 TEST RESULTS 1 OF HPCS SYSTEM STATUS

	A1	A2	M	P	HPCS	Vessel
V_i	1	0	0	0	0	0
V_1	0.500000	0.006693	0.006693	0.500000	0.006693	0.006693
V_2	0.466586	0.006262	0.006262	0.466586	0.006693	0.006919
V_3	0.467376	0.008715	0.008715	0.467376	0.009354	0.009638
V_4	0.454598	0.008420	0.008420	0.454598	0.009293	0.009689
V_5	0.455342	0.009557	0.009557	0.455342	0.010565	0.010992
V_6	0.449336	0.009367	0.009367	0.449336	0.010496	0.010980
V_7	0.449907	0.009944	0.009944	0.449907	0.011148	0.011648
V_8	0.446845	0.009824	0.009824	0.446845	0.011090	0.011620
V_9	0.447249	0.010131	0.010131	0.447249	0.011436	0.011974
V_{10}	0.445627	0.010055	0.010055	0.445627	0.011393	0.011946
V_{11}	0.445900	0.010222	0.010222	0.445900	0.011580	0.012137
V_{12}	0.445023	0.010175	0.010175	0.445023	0.011550	0.012115
V_{13}	0.445201	0.010266	0.010266	0.445201	0.011652	0.012219
V_f	0.5	0	0	0	0	0

Applying the interpretation specified and taking into consideration the meaning of the value 0 and the value 1, also specified in section 4.5, a potential future scenario results in which the HPCS system fails (represented by 0) and the vessel malfunctions (represented by 0).

These results were compared to expert analysis, and found to be consistent in all particulars.

C. Test Scenario for the Small LOCA Accident

The system analyzed in the second phase is part of the mitigating system (analyzed in phase 3) to achieve reactor stability; phase 2 is a sub-phase of phase 3. Therefore, to mitigate the negative effects of the phase 2 result, it is necessary to enter the simulation of phase 3 using the test scenario for a small LOCA accident (accident due to a small loss of coolant). In this scenario, the analysis of the mitigating system is conducted through the third FCM; the second FCM feeds the third FCM.

The small LOCA accident is represented by a vector indicating the presence or absence of a series of events related to the system which will mitigate the negative effect of the small LOCA accident.

There is an event implicit in the sixteen events related in this scenario, ***containment ok***, which is present when there is no containment vented, fugue, failed, or vulnerable, i.e., when there is no degree of failure in the containment, it is assumed to be "OK.

The initial vector for this scenario indicates the presence of P, 01, and HPCS, which correspond to the events relief valve operational, manual valve to trigger condenser operational, and HPCS system operational, respectively. The test results 1 of small LOCA are shown in Table 12.

TABLE 12 TEST RESULTS 1 OF SMALL LOCA.

	P	01	SS	HPCS	RCIC	X1	V	W	Y	R	SUR	CG	VT	FG	FL	VN
V[0]=	1.00000	1.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
V[1]=	0.99330	0.50000	0.00004	0.50000	0.00669	0.00669	0.00669	0.50000	0.50000	0.50000	0.50000	0.99974	0.00026	0.00026	0.00026	0.00005
V[2]=	0.92412	0.49994	0.00057	0.82476	0.07586	0.07822	0.07822	0.00286	0.07576	0.07576	0.29934	0.99995	0.00056	0.00056	0.00000	0.00000
V[3]=	0.92392	0.49928	0.00081	0.61973	0.01592	0.02337	0.02337	0.35204	0.40640	0.40640	0.83694	0.99964	0.00161	0.00161	0.00075	0.00000
V[4]=	0.92360	0.49899	0.00081	0.79184	0.04316	0.04825	0.04825	0.00133	0.11549	0.11549	0.47233	0.99999	0.00079	0.00079	0.00001	0.00000
V[5]=	0.92350	0.49898	0.00081	0.72144	0.01872	0.02371	0.02371	0.13301	0.35949	0.35949	0.83798	0.99979	0.00220	0.00220	0.00069	0.00000
V[6]=	0.92350	0.49898	0.00081	0.78901	0.02641	0.02963	0.02963	0.00210	0.14173	0.14173	0.72802	0.99997	0.00168	0.00168	0.00004	0.00000
V[7]=	0.92349	0.49898	0.00081	0.77233	0.01898	0.02195	0.02195	0.03154	0.32984	0.32984	0.83745	0.99993	0.00249	0.00249	0.00060	0.00000
V[8]=	0.92349	0.49898	0.00081	0.79175	0.02060	0.02293	0.02293	0.00283	0.16081	0.16081	0.81641	0.99996	0.00234	0.00234	0.00008	0.00000
V[9]=	0.92349	0.49898	0.00081	0.78878	0.01873	0.02096	0.02096	0.01688	0.30906	0.30906	0.83696	0.99995	0.00256	0.00256	0.00051	0.00000
V[10]=	0.92349	0.49898	0.00081	0.79359	0.01900	0.02106	0.02106	0.00349	0.17539	0.17539	0.82714	0.99996	0.00244	0.00244	0.00011	0.00000
V[11]=	0.92349	0.49898	0.00081	0.79320	0.01856	0.02058	0.02058	0.01386	0.29369	0.29369	0.83651	0.99996	0.00257	0.00257	0.00044	0.00000
V[12]=	0.92349	0.49898	0.00081	0.79434	0.01859	0.02057	0.02057	0.00408	0.18684	0.18684	0.82929	0.99996	0.00245	0.00245	0.00013	0.00000
V[13]=	0.92349	0.49898	0.00081	0.79433	0.01849	0.02045	0.02045	0.01225	0.28194	0.28194	0.83610	0.99996	0.00257	0.00257	0.00039	0.00000
V[14]=	0.92349	0.49898	0.00081	0.79460	0.01849	0.02044	0.02044	0.00459	0.19597	0.19597	0.83043	0.99996	0.00246	0.00246	0.00014	0.00000
V[15]=	0.923497	0.498982	0.000814	0.79462	0.01847	0.02041	0.02041	0.01112	0.27277	0.27277	0.83575	0.999959	0.00256	0.00256	0.000357	0.000000

The interpretation of these test results by applying the specified criteria indicates that the future status of events is as follows: P remains in good condition, manual valve 01 has the potential to do the same, and HPCS is operational. CG, as is the containment, because VT, FG, FL, and VN do not appear, which is assumed to indicate a containment in good condition.

IX. CONCLUSIONS FROM ANALYSIS, TESTS, AND RESULTS

The objective pursued when the nuclear plant enters into a small LOCA scenario is to guarantee adequate cooling of the core, mitigating the effect of the initiating event: a small loss of coolant. This coolant is used to keep the core within the temperature range necessary for it to operate under normal conditions. In the case study, it is evident that all events are involved in attempts to mitigate the effects of the loss of coolant [22-26]. Therefore, our aim is to provide an analysis which allows the establishment of possible mechanisms to mitigate failures before their effects can affect the containment and the core itself. This anticipates a potential scenario and the actions necessary to prevent serious accidents to the greatest possible extent. This is one of the innovative characteristics, at the predictive level, that fuzzy logic offers by establishing relationships of causality via fuzzy cognitive maps.

In this paper we developed an exhaustive methodology for the analysis and design of the behavior of an event [22-26], represented by a cognitive model. Thus, the system produces consistent results according to the standards in the diagnosis of accidents like small LOCA in a nuclear power plant.

It is important to observe that many of the behaviors are superimposed, and allow for the trigger of a cascade of FCMs. This is important because the cognitive model achieved an abstraction of behaviors according to level. This facilitates the design of such maps and allows the establishment a hierarchy for nested behaviors. It is also interesting to observe how a network of causalities among themselves forms the different actions taken depending on the different elements that comprise a given behavior. In fact, those elements may or may not be present in the environment. This requires the ability to model reactive behaviors in dynamic and uncertain environments. This is achieved by reading the events that make up the ongoing scenario, and offers an added advantage by allowing the encapsulation of behaviors in reactive agents that allow for reading of events that trigger their actions in dynamic environments, and by extension the possibility of multi-agent systems.

The approach used contrasts strongly with the de-analytic methodology currently used in the Fig. 1, in which event trees are developed using knowledge and experience acquired for other similar reactors [22-26]. In this case the approach is important in that it allows the development of a rapid mechanism of reasoning which entails uncertainty.

On the other hand, one of the advantages fuzzy logic offers as a tool in knowledge representation is that it provides a potential future scenario based on an initial failure, allowing automatic relation of mitigating actions. In the case study, it constitutes an aid to decision-making processes in risk situations by reducing error on the part of the human working under the pressure of a potentially serious accident scenario.

As a final point, we propose an analysis and design that can be used to implement decision-making processes that can simulate human behavior. The analysis and design developed in this work can be applied to other domains, such as the results of narrative, video games, and the process of decision-making for a pedagogical agent [18, 21].

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